

Refractivity from Clutter and Refractivity Data Fusion

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LONG-TERM GOALS

The long-term goals of this research are to provide accurate mesoscale analyses and forecasts of microwave refractivity (M), and to quantify the impacts of refractive effects upon Naval communications and weapons systems. Such refractive effects are of particular importance to strike warfare, ship self-defense, special operations, and potentially to directed energy capabilities.

OBJECTIVES

The objectives of this research are to enhance numerical weather prediction approaches to analyzing (nowcasting) and forecasting microwave refractivity and the concomitant refractive effects upon Naval combat systems and communications.

APPROACH

The approach used is multifaceted and multi-disciplined. The Navy's Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS®)¹ is applied with high horizontal and vertical resolution, and is used to analyze and forecast refractivity structure. Further, COAMPS provides background fields for implementing data fusion techniques to improve refractivity analyses, and inversion techniques such as used in extracting Refractivity-From-Clutter (RFC). To refine and validate this approach, datasets from several field experiments, some including special electromagnetic (EM) propagation data, have been exploited. The Variability of Coastal Atmospheric Refractivity experiment (VOCAR) data provided a test bed for validating the refractivity data fusion methodology. Dropsonde data from the second Dynamics and Chemistry of Marine Stratocumulus Experiment (DYCOMS-II) provided observations to test sensitivity of the model-predicted M fields to changes in boundary layer parameterizations and vertical resolutions. The Wallops-2000 Experiment (April/May 2000) consisted of EM propagation loss measurements along radial paths away from the coast in conjunction with near-surface meteorological measurements (Stapleton et al. 2001). We have received Wallops-2000 data from several sources that participated in that field experiment (Dr. Rob Marshall, NSWCDD; Dr. Ken Davidson, NPS; Dr. Ross Rottier, Johns Hopkins APL) and have supplied COAMPS fields and statistics to those groups as well as collaborators from SPAWARSSYSCEN, San Diego (Dr. Michael Jablecki and Mr. Ted Rogers). We are continuing to foster collaboration among the various groups as we plan future field programs and projects to further develop COAMPS forecast refractivity capability.

¹ COAMPS® is a registered trademark of the Naval Research Laboratory.

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One of the key goals of this project was to improve analyses of the refractivity field using a data fusion technique. This technique seeks to improve model fields of modified refractivity (M). The fusion algorithm modifies a model analysis profile of refractivity at the time and location of an observed profile so as to more closely match the sounding by comparing a large number of randomly generated shifts in elevation and M units. The set of elevation shifts and M shifts which most closely matches the observed sounding is then distributed over a user-defined radius of influence R. A linear weighting is then applied such that the influence of the shifting decreases to zero at R. When the distributed and weighted field of shifts is applied to the model M field, a new three-dimensional model M field is produced.

We have also analyzed COAMPS performance for a plethora of synoptic environments and geographic settings, in regions of Naval interest such as the seas surrounding the South Korean Peninsula. Month-long series of forecasts were conducted to assess 3D refractive conditions and establish ducting “climatologies” for that region as well as for U. S. West Coast and Wallops Island, VA. In the process of undertaking this research, we have consolidated fields from the various COAMPS forecasts and made them available on the MEL database to the scientific community for wide dissemination and use.

WORK COMPLETED

1. High-resolution COAMPS forecasts for a full 1.5 months of the Wallops-2000 field experiment have been performed and hourly fields archived on the Master Environmental Library (MEL), which is sponsored by the Defense Modeling and Simulation Office (DMSO) and is available for use by the scientific community at <http://mes.dms.o.mil>. Individual case studies were performed using the forecasts and observational data. Model fields and statistics comparing COAMPS forecasts with Wallops-2000 observations have been compiled and distributed to the collaborative groups.
2. Month-long series of COAMPS 12-hr forecasts were performed for a domain centered over the Sea of Japan to assess refractive structures during summer and winter seasons in this region. The full suite of COAMPS fields has been ported to the MEL database.
3. Average ducting conditions such as duct base height, strength, thickness, surface based ducting and evaporative ducts over the Sea of Japan, East China and Yellow Sea have been computed and analyzed. Individual case studies have been examined to determine preferred regions of ducting and ducting characteristics with respect to the synoptic pressure patterns, frontal locations and interaction with the surrounding coastal topography.
4. COAMPS refractivity forecasts were run for the entire period of DYCOMS-II at several different horizontal and vertical grid resolutions; with the results extensively verified against aircraft dropsondes data.
5. The data fusion algorithm has been validated using data from the VOCAR experiment using both single and dual base-point simulations. Statistics documenting the performance of the data fusion approach were compiled
6. In preparation for transition to operations, the data fusion algorithm has been converted to FORTAN 90 and is undergoing evaluation.

7. The PI of this project co-chaired a session at the international IEEE/URSI Radio Science meeting held June 2004 in Monterey.

8. This work has been presented at several conferences including two meetings in January: the AMS Annual Meeting in San Diego and the Annual URSI Radio Science meeting in Boulder. Two additional papers are to be given at the BACIMO conference in Monterey this October.

9. In addition to publishing the Wallops-2000 findings in an NRL Review paper, two journal articles are in preparation stemming from research accomplishments: one discussing the seasonal variability of refractivity conditions along the U.S. West Coast and the other focusing on the high-resolution model results from the Wallops-2000 Field Program. Each provided forecasting challenges in representing the spatial and temporal inhomogeneity of refractive conditions in the littoral.

RESULTS

Computation of ducting products such as duct strength, duct thickness, and duct base height from COAMPS has been transitioned and are now operational products at FNMOC and the on-scene version of this model [COAMPS-OS]. Fig. 1 displays a schematic that defines the terminology associated with a profile of modified refractivity, and Fig. 2 shows an example COAMPS forecast on a 27 km grid of duct base height over the Arabian Sea and Indian Ocean region. This figure shows near-surface based ducting over portions of the Red Sea and the Arabian Gulf, with regions of elevated ducting in the Arabian Sea and scattered over the Indian Ocean. While plots such as this clearly are of value, there often is need for higher resolution, more site-specific information. While mesoscale models such as COAMPS are very capable of supplying such high-resolution forecasts, their fidelity and reliability over a range of challenging meteorological conditions must be established. This has been a primary task of this project.

In previous years, we utilized COAMPS and the Wallops-2000 data set to examine refractivity structure and propagation conditions associated with major coastal synoptic events that included warm and cold frontal passages, and on the impact of local and mesoscale coastal circulations, as well as the alteration of propagation conditions associated with large SST gradients in the vicinity of the Gulf Stream. Fig. 3 shows the dramatic evolution of the marine layer over a 2-hour period during 7 April 2000. In Fig. 3a, the subsiding return flow within the afternoon sea-breeze circulation suppresses and tightens the inversion to strengthen ducting while the warm, moist air over the Gulf stream provides a less favorable environment for trapping EM energy. Two hours later, trapping is confined to near the coastline as a warm front ushers in a deep moist layer from the south eliminating the moisture inversion and much of the low-level ducting.

The complete suite of COAMPS fields for the duration of the Wallops-2000 Field program is contained on the MEL web server (<http://mes.dms.o.mil>). When coupled with the observational and propagation data collected for the experiment, it provides a powerful tool not only for model validation, but also for individual studies of complex coastal air-sea interaction affects upon EM propagation. Figs. 4-6 demonstrate the verification of various forecast parameters against the observations. Statistical measures give COAMPS forecast capability in evaporation duct height (EDH) determined from analysis of the time series over the full 1.5-month study period and yield background EDH errors useful for the RFC technique (Fig. 4). Fig. 5 reveals the rapid development of a surface-based duct captured aboard an instrumented helicopter on 4 May 2000 and the corresponding

M profile forecast by COAMPS. Here the temporal trend in the refractivity profile is consistent with observations but the duct strength is under-forecast. Assessing the model's fidelity in forecasting refractive structures yields greater confidence in the spatially inhomogeneous fields used for predicting propagation factor, which measures the difference in received signal power vs. standard propagation and is routinely used in Naval operations to assess signal ranges and detection. Fig. 6 compares the directly measured propagation factor for a C Band Radar to that obtained from COAMPS fields showing differences of less than ~ 10 dB within 16 nautical miles of the coast. In this case, we can see over the horizon for slightly super-refractive propagation, but COAMPS is under-predicting how well.

In order to improve COAMPS 3D refractivity fields required to determine ducting and assess the propagation environment, we implemented a refractivity data fusion technique. The methodology was tested with data from the VOCAR experiment, which took place in August 1993 in the southern California Bight. Fig. 9 shows a schematic diagram of the profile shifting procedure used in the data fusion algorithm. In the first set of tests, soundings and model profiles from the location of the Naval Postgraduate School (NPS) research ship were used to generate the field of elevation and M shifts (see Fig. 10 for locations). The field of shifts was then applied to the model M field and the impact was assessed at San Nicholas Island, Point Vicente, and San Clemente Island (Fig. 11). A statistical analysis of results over the entire VOCAR period is shown in Table 1. Note that the method yields a 26% improvement in duct base height estimates. The improvement in delta M is somewhat more modest. In the second set of test, soundings and model profiles from both the NPS ship and San Clemente Island were used to generate the field of shifts, assessed at San Nicholas Island and Pt. Vicente. The statistics were not significantly different from the single sounding results. We also assessed the sensitivity of the method to changes in the radius of influence and the vertical resolution of the computational grid to which the sounding and model data are interpolated.

The COAMPS forecasts have been valuable at providing general ducting characteristics over several regions of interest. Averages of the 3D refractivity field from month-long series of 12-hr forecasts have illuminated patterns and variability in ducting conditions associated with complex mesoscale interactions. In addition to the Wallops Island location, studies over the U.S. West Coast and Sea of Japan have revealed sensitivity to intricacies of the coastal topography/land-sea boundary, inhomogeneity in the surface forcing, and changes in the prevailing wind direction. Fig. 7 shows the monthly averaged duct strength and duct base height for four months in each season of 1999. In addition to the spatial variability apparent in these mean fields, the patterns indicate seasonal transitions in ducting such as the strengthening of ducts in the Southern CA Bight and the lowering of duct base heights to near surface-based along the coast in October. Near South Korea, preferred regions of ducting during winter and summer are assessed from averages of COAMPS forecasts for May/June 1999 and January/February 2000. In winter for example, EM trapping layers occur ~ 10 -20% of the time over the Yellow Sea and far western Pacific (Fig. 8) forming below post-frontal cold, dry air advecting over the warmer waters of the Kurishio current.

While monthly averages provide general characteristics and seasonal trends of trapping conditions, study of individual forecast periods is necessary to quantify the model's daily performance, weaknesses and limitations. We have performed analyses of profiles of modified refractivity, mixing ratio, and potential temperature from COAMPS and from the verifying dropsonde soundings from DYCOMS-II research flights, which took place in July 2001 over the NE Pacific Ocean, approximately 300 km west of San Diego, CA. In general, the duct base height is well forecast but the

strength of the duct tends to be under-forecast. The structure of the boundary layer is captured well by the model in most cases.

Statistical analysis of the results shows that the bias in duct base height is -46 m (the model is 46 m too low in the mean) and the average duct base height is 746 m. The average delta M is 26.2 and the bias is -7.3 . We also conducted sensitivity studies to assess the impact of both vertical resolution and variations in sea surface temperature on refractivity forecasts. In addition to providing a better refractivity analysis via the data fusion technique, other recent improvements to COAMPS will indirectly benefit its prognostic capability in EM propagation, such as a new data assimilation system, higher resolution SST analyses and more advanced physical parameterization schemes.

IMPACT/APPLICATIONS

Strike warfare, ship self-defense, special operations, and basic Naval communications and surveillance can all be strongly impacted by EM refractive effects. This project addresses both high-resolution numerical weather prediction of refractivity and the implications of the predicted refractive state for EM propagation/Naval operations. The new capability to map radar-ducting parameters over a mesoscale domain from COAMPS analyses and/or forecasts has been transitioned to FNMOC. A technique for augmenting 3D refractivity fields has been developed and tested by fusing existing model profiles with observationally determined shifts to better represent the observed duct characteristics. Validation and refinement of forecast refractivity structure over a wide-range of synoptic conditions has provided improved background ('first guess') fields for the RFC inversion technique. Improvements in knowledge of refractivity conditions from RFC are expected to permit optimization of radar performance. The PI of this effort recently participated in a High Power Microwave Predictive Avoidance Project kickoff meeting lead by NAVAIR China Lake and hosted by the Naval Air Weapons Station at Pt. Mugu.

TRANSITIONS

Software within COAMPS that permits the computation and graphical display of EM ducting characteristics over a mesoscale domain has been transitioned to FNMOC and support is being continued, which includes the use of COAMPS-OS. Code refinements to the calculation of the evaporation duct height in stable conditions have been implemented. Month-long, high-resolution COAMPS forecast databases have been established on MEL for the Wallops-2000 Field program and Sea of Japan study. Evaluation of the FORTRAN 90 data fusion algorithm is underway to transition the product to operations.

RELATED PROJECTS

The 6.2 Refractivity-from-Clutter program (PI: Ted Rogers) at SPAWARSYSCEN, San Diego has been closely linked to the work in this project. Model development improvements to COAMPS (particularly those relating to boundary layer and moist physics), such as 6.2 Advanced Moist Physics Modeling (NRL base), 6.2 Improved COAMPS Land Boundary Layers (NRL base), and 6.2 Advanced Surface Flux Parameterization (ONR funded) are important to this project.

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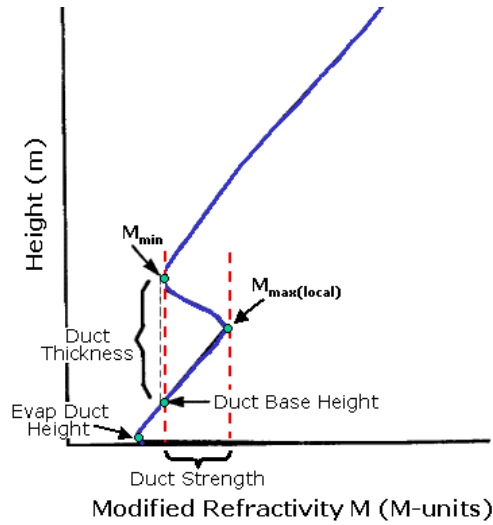


Figure 1. Schematic of a modified refractivity (M) profile. [graph: vertical variation of modified refractivity with height for a typical marine boundary layer profile labeled with key parameters that affect EM propagation. M increases with height except for trapping layers for which the gradient in M is negative. The evaporation duct height is a surface duct represented by the height above the surface where M first begins to increase. For elevated ducts, the difference between M at the top and bottom of the trapping layer is the duct strength and the duct thickness and duct base height are determined by sampling the M profile below the top of the trapping layer to find the height where M equals M at the top (M_{min}).]

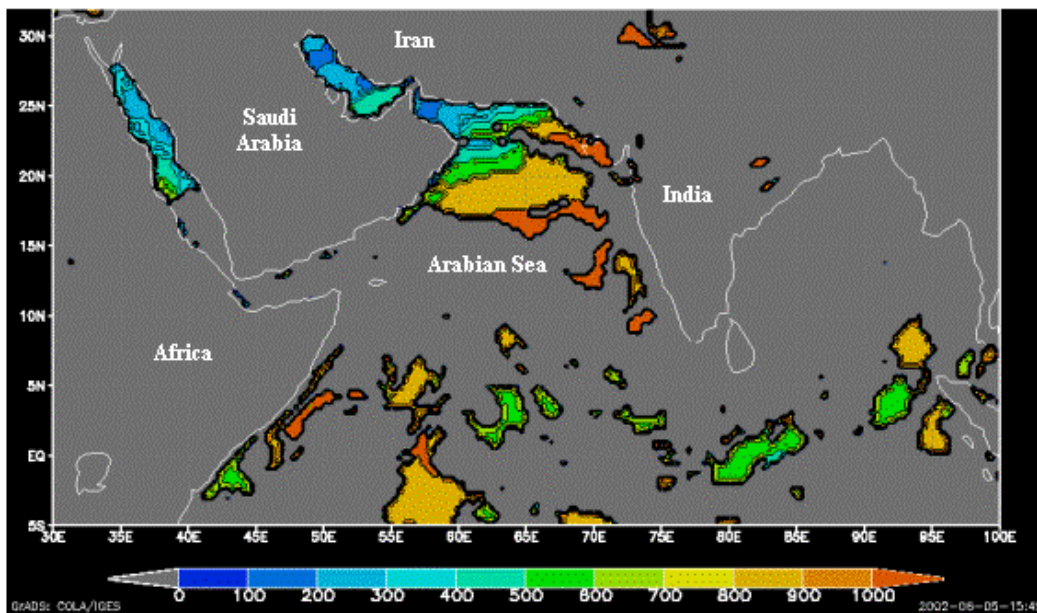


Figure 2. COAMPS forecasts of duct base height (DBH; m) in the Arabian Sea. An example of a graphical product disseminated by FNMOC and used operationally to assess regional ducting. [graph: Color shading of the DBH indicates surface based ducting in the Arabian Gulf and Red Sea with elevated ducting in portions of the Arabian Sea and Indian Ocean.]

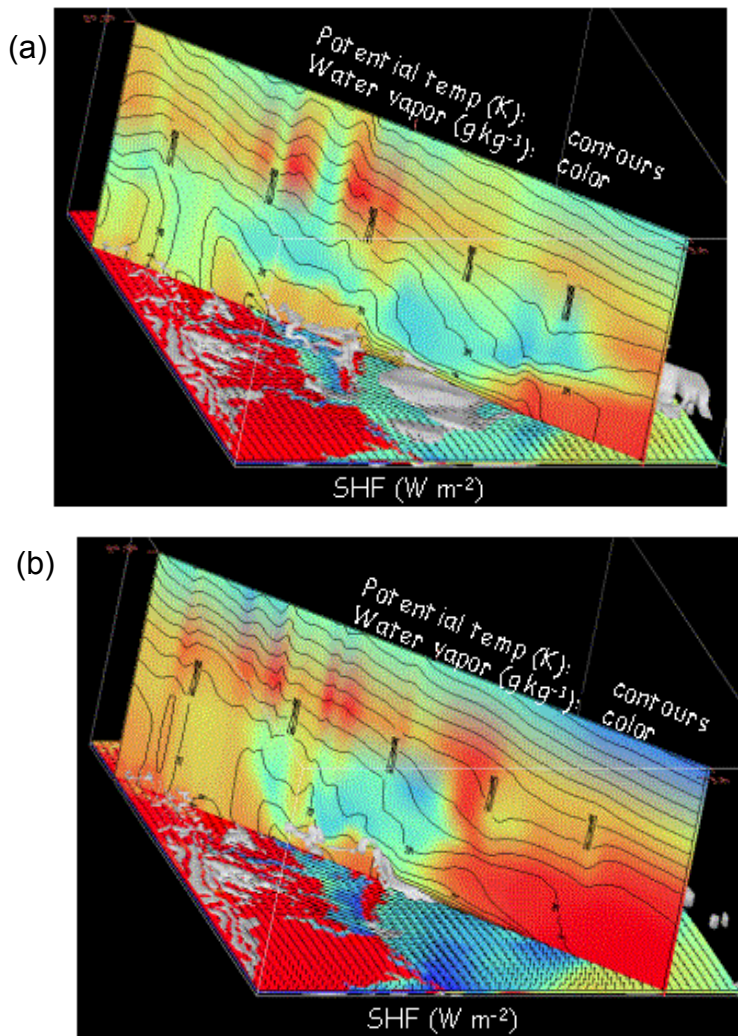


Figure 3. Cross-sections of potential temperature (contours; K) and water vapor (color; g kg^{-1}) at 1300 LT (a) and 1500 LT (b) 7 April 2000. White ‘clouds’ indicate regions of EM trapping. The horizontal plane shows near-surface wind arrows and the surface sensible heat flux (color; W m^{-2}). [graph: Color shading of water vapor in a cross-section extending perpendicular to the coast through Wallops Island, Virginia reveals a warm, moist layer advancing into the domain from the south that weakens the low-level moisture inversion necessary for trapping. Trapping is eliminated within the moist layer behind the warm front.]

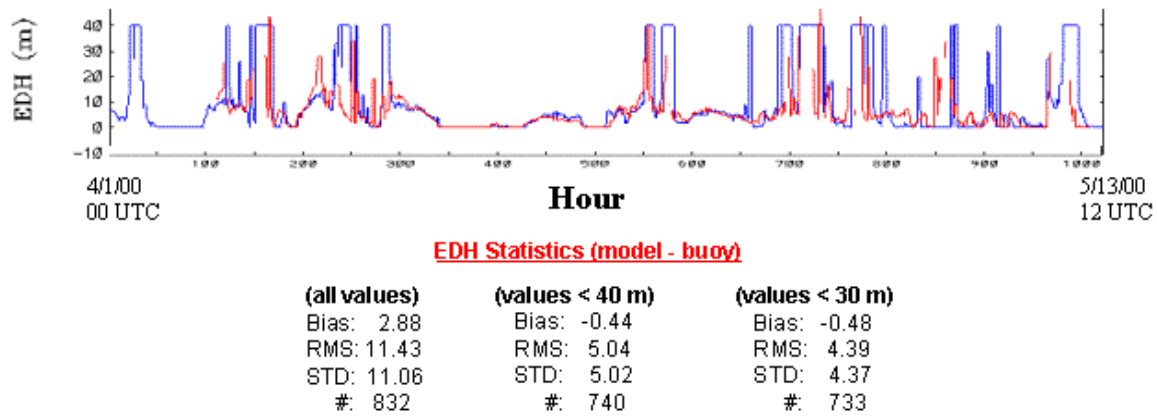


Figure 4. Time series of evaporation duct height (EDH) for the Wallops-2000 Experiment (April/May 2000) at the NPS buoy location ~7 km from shore computed by COAMPS (blue) and from NPS buoy observations (red). [graph: Bias and RMS error statistics are given using all values, and using only EDH values below the upper threshold value of 40 m. Time series of the model EDH shows that most mid-range values of EDH are in good agreement with observations.]

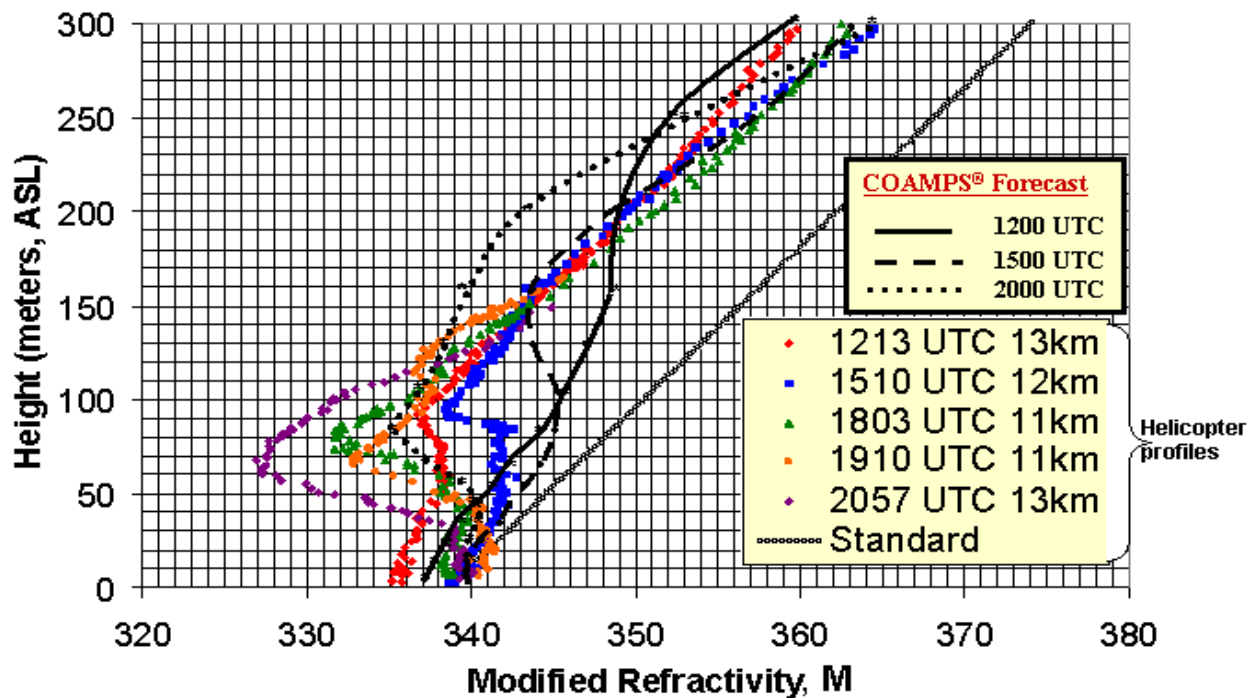


Figure 5. Vertical profiles ~12 km from shore of modified refractivity (M) measured by helicopter (colored symbols) and forecast by COAMPS (black lines) between 12 and 20 UTC 4 May 2000. [graph: observed M profile at ~12 UTC has a weak duct (~2 M-units, top at 100 m) that lowers, strengthens and becomes surface based by ~18 UTC (~8.5 M-units, top at 80 m), continuing to lower and strengthen at ~21 UTC (12 M-units, top at 70 m). The model has the same overall trend but has a weaker and higher duct (2 M-units, top at 150 m at 18 UTC; ~6 M-units, top at 85 m at 20 UTC).]

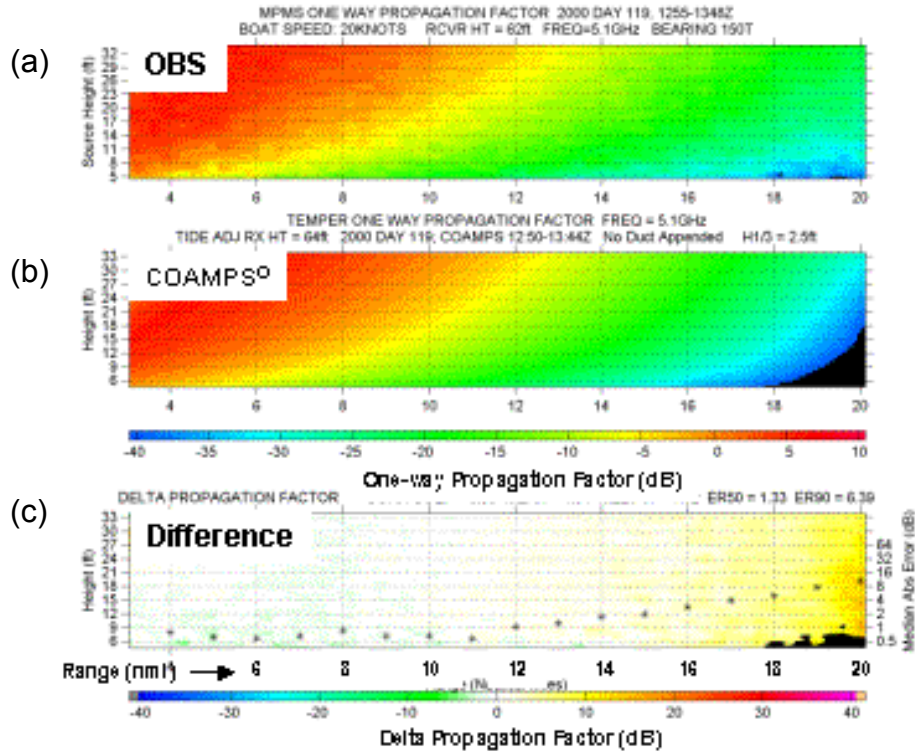


Figure 6. Example of a radar cross-section of propagation factor for a C Band (5.1 GHz) radar on 28 April 2000 using the TEMPER model (courtesy of Rob Marshall, NSWC Dahlgren). Propagation factor (PF) directly measured at a shore-based receiver from a transmitter aboard a boat moving along a radial away from the coast (a), PF obtained from COAMPS fields along the same path (b) and the difference (c). [graph: The propagation factor gives the difference between the signal power at the location and the signal power at the location when standard propagation is considered. Both observed and modeled propagation factor indicate slightly super-refractive conditions with no ducting, but COAMPS under-estimates by ~10 dB at 15 nautical mi how far over the horizon detection ranges are enhanced.]

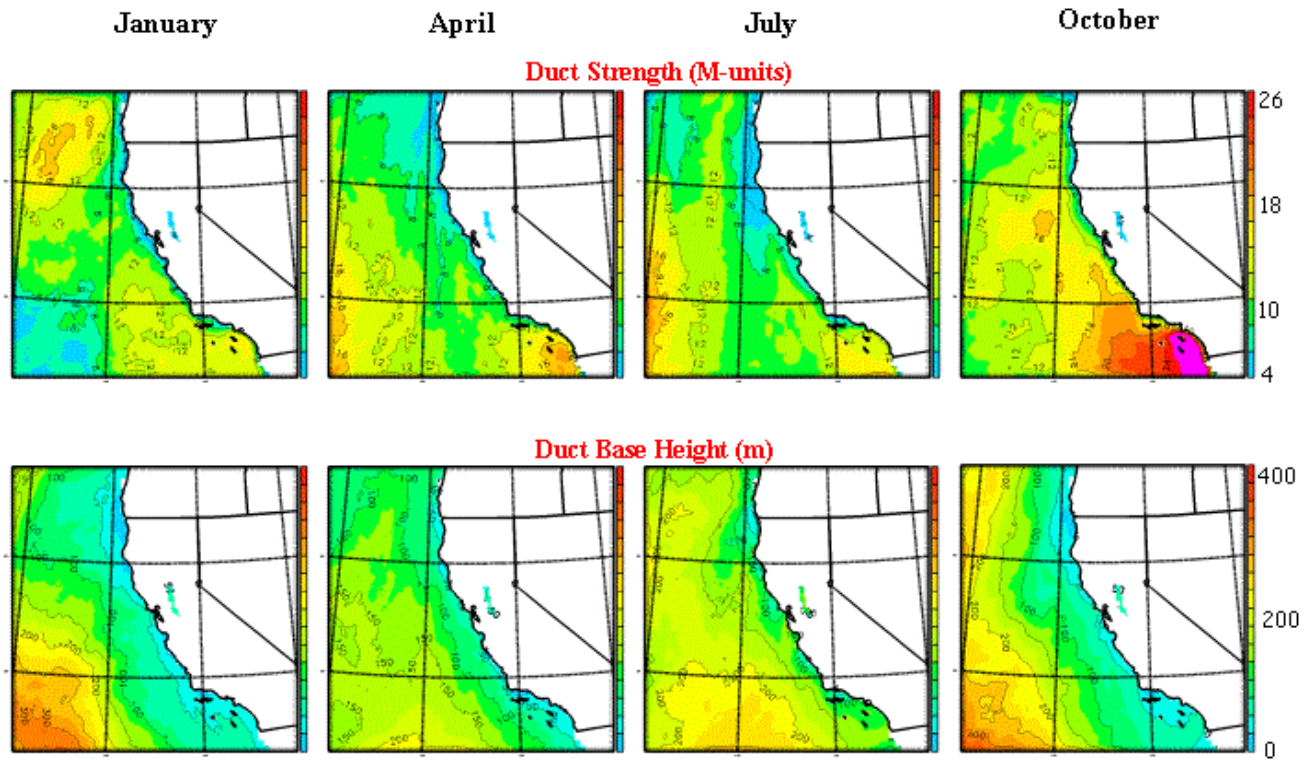


Figure 7. Monthly averaged duct strength (DS, M-units) and duct base heights (DBH, m) along the U.S. West Coast for January, April, July and October 1999. [graph: Color shading of DS show that the strongest ducts occur in the Southern CA Bight and in the month of October ($DS_{max} = 28$ M-units) while the north coast (OR/CA boarder) has much weaker ducts especially in spring and summer ($DS_{min} = 5$ M-units compared to $DS_{max} = 12-16$ M-units offshore and in the Bight). Duct base heights slope up away from the coast with surface based ducting more likely along the north coast and elevated ducts in the SW part of the model domain (near $30^{\circ}N$, $130^{\circ}W$). In fall/winter the slope is greater than spring/summer with a tendency for surface-based ducting from Cape Mendocino to northern OR sloping to an offshore DBH in the SW near 300 m. In spring and summer, coastal DBH are near 100 m sloping to an offshore height in the S near 200m.]

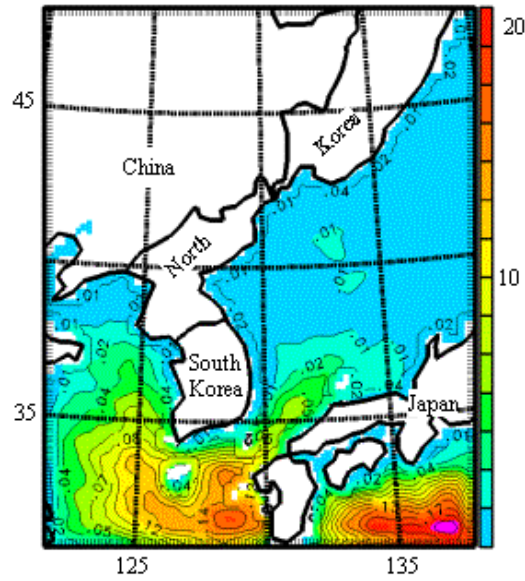


Figure 8. January 2000 duct frequency (%) over the seas surrounding the Southern Korean Peninsula from hourly COAMPS forecasts. [graph: Ducting occurs less than 1% of the time in the Sea of Japan and ~10-20% of the time in the southern part of the domain (i.e. to the west and south of Japan between 30-35°N and 125-137°E).]

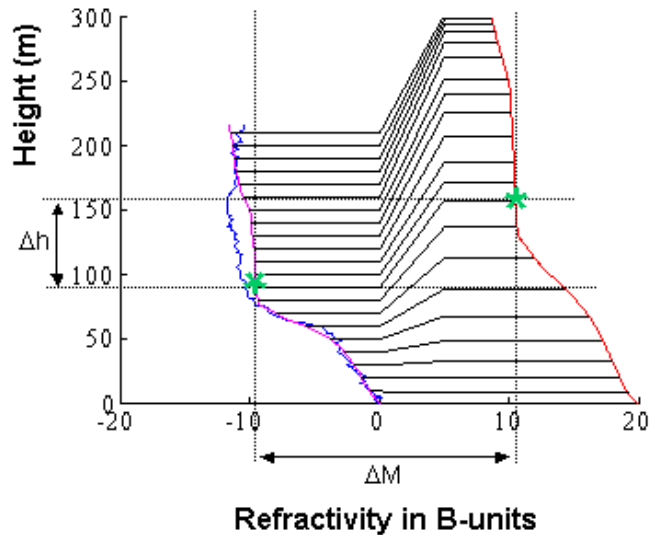


Figure 9. Schematic of the shift imposed upon an original COAMPS refractivity profile by the data fusion technique. [graph: red is the original COAMPS profile decreasing from 20 to 10 B-units over 300 m depth, blue is sounding decreasing from 0 to 10 B-units over a 200 m depth, and pink is modified COAMPS which is close to the observed sounding. The two green asterisks indicate a point on the original profile and the corresponding point on the shifted profile obtained by using a refractivity shift of $\Delta M=20$ B-units and a height shift of $\Delta h=65$ m.]

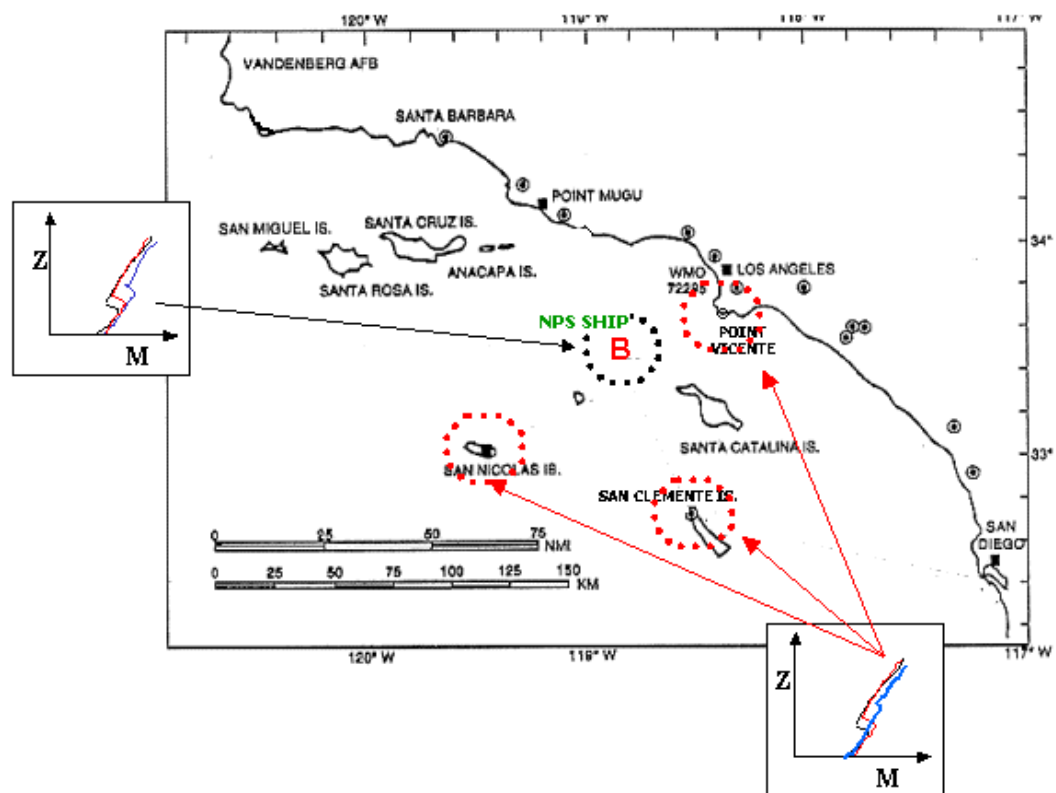


Figure 10. Map of the VOCAR domain in the Southern CA Bights. graph: The NPS ship located at (33.5°N, 118.8°W) is the base point (B) from which the shifts are determined and three surrounding points (red circles) are locations for which the modified profiles are compared to soundings.]

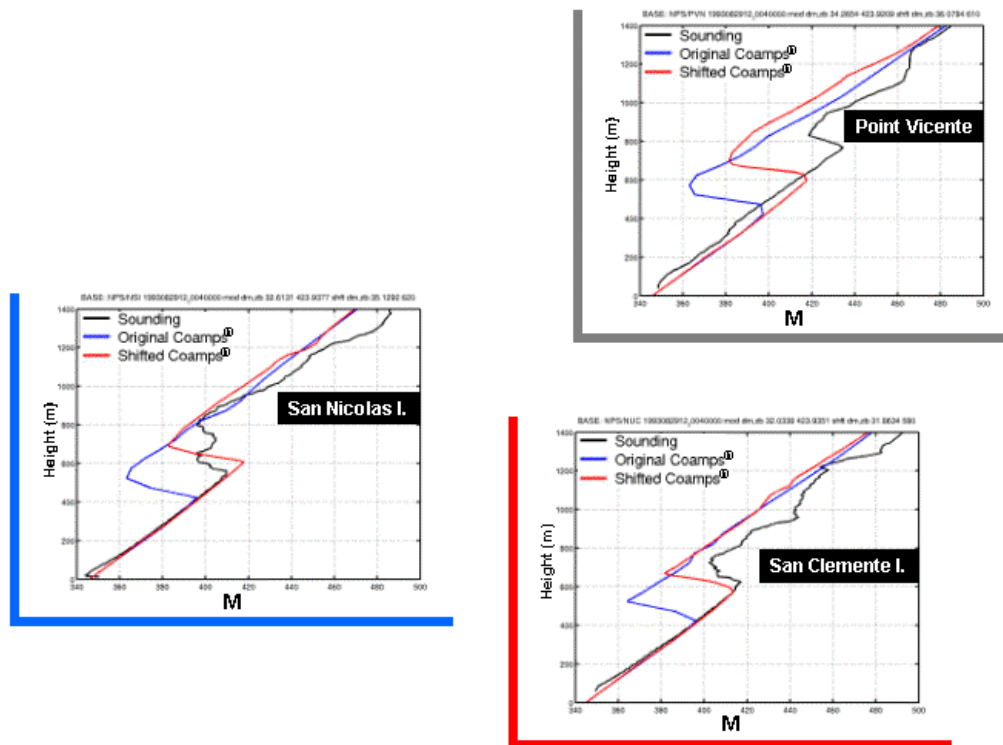


Figure 11. Refractivity profiles at three locations using shifts from the NPS ship. [graph: The black line is the sounding showing a higher and weaker duct than is predicted by COAMPS (blue line), and the red line is the modified COAMPS profile which is shifted to better match the observed sounding.]

Table 1: Statistics from data fusion VOCAR test bed showing the improvement in DBH and DS with the shifted COAMPS refractivity profiles.

	50 Soundings	Original COAMPS®	Shifted COAMPS®
<DBH>	476 m	522 m	451 m
DBH-Bias	---	46 m	-25 m
< ΔM >	28	33	31
ΔM -Bias	---	5	3
	Soundings/ Orig. COAMPS®		Soundings/Shifted COAMPS®
RMSE ¹ (DBH)	189 m		139 m
RMSE(ΔM)	23		21